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Procedia Engineering 10 (2011) 1360–1365

Engineering Procedia

ICM11

Effect of Al and Al-Si diffusion coating on the low cycle fatigue behavior of Inconel 713LC

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Abstract

Cylindrical specimens of Inconel 713LC in untreated condition and surface treated with Al and Al-Si diffusion coating were cyclically strained under strain control at 800 °C in air. The structural and hardness characteristics of the hardened surface layer are presented. Cyclic hardening/softening curves, cyclic stress-strain curves, and fatigue life curves are obtained. The sections parallel to the specimen axis have been examined to study fatigue damage mechanisms. The effect of Al coating on stress response and fatigue life slightly differs from that of Al-Si coating.

Keywords: Low cycle fatigue; Inconel 713LC; diffusion coating; cyclic hardening/softening curve; cyclic stress-strain curves; fatigue life curve;

1. Introduction

Diffusion coatings based on simple and modified aluminides are widely used to improve high temperatures oxidation and corrosion resistance of nickel based superalloys that are the most important materials for the critical components of gas turbines for power generation and aerospace and marine propulsion. Diffusion coating processing results in changes in material properties both the surface layer and the substrate. Particularly, fatigue properties are quite sensitive to surface treatments.

Both beneficial and detrimental effects of Al and Al-Si diffusion coatings on fatigue life of nickel based superalloys are reported [1-3]. In an Al diffusion coating of polycrystalline René 80, detrimental

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Selection and peer-review under responsibility of ICM11 doi:10.1016/j.proeng.2011.04.226

effect is reported at high strain amplitudes while fatigue lives are longer at low strain amplitudes in comparison with the uncoated material [1]. Different fatigue damage mechanisms were found in directionally solidified nickel-base superalloy with Al-Si diffusion coating at different temperatures in the interval from 500 to 700 °C [2]. The latter surface treatment applied on cast Inconel 713LC resulted in the fatigue life increase both in Manson-Coffin and Basquin representation at 800 °C [3].

In the present paper, the influence of the surface treatment by the Al-Si diffusion coating on the fatigue behavior of cast Inconel 713LC is studied. The fatigue life, the cyclic stress-strain response and fatigue damage mechanisms are investigated.

2. Materials and experimental procedures

The polycrystalline superalloy Inconel 713LC was provided as conventionally cast rods by PBS, Velká Bíteš a.s. Chemical composition of the material is shown in Table 1. Polished sections of the material reveal coarse grains with dendrites, carbides and shrinkage pores being rarely up to 0.4 mm in diameter. Rugged grain boundaries due to the complex dendritic structure are apparent. The average grain size, found using the linear intercept method, was 2.3 mm.

Table 1. Chemical composition of Inconel 713LC (in wt.%)

Cr	Al	Mo	Nb	Ti	Zr	Co	Fe	Ta	Mn	Si	Cu	C	B	P	S	Ni
11.85	5.80	4.54	2.27	0.72	0.11	<0.05	<0.05	<0.05	<0.05	<0.05	0.05	0.04	0.015	0.006	0.004	Bal.

Fatigue tests were performed on cylindrical button-end specimens having gauge length and diameter of 15 and 6 mm, respectively. Specimens were machined parallel to the rod axis and their gauge length was mechanically ground. One group of specimens was surface treated with Al diffusion coating. The CVD technique was applied to provide aluminizing of the specimen surface [4]. The deposition temperature and time were 1050 °C and 5 hours, respectively. Three specimens were surface-treated using a slurry technique. A suspension of Al and Si was deposited over the gauge length and the specimens were annealed at 950 °C for 5 hours.

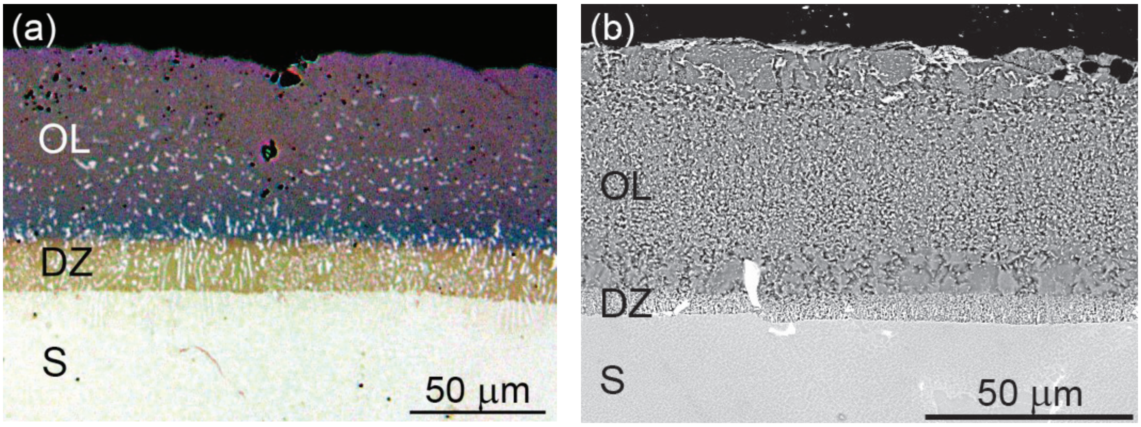

Fig. 1. Microstructure of as-coated specimens in the section perpendicular to the specimen surface. Outer layer (OL), diffusion zone (DZ), and substrate (S). (a) Al diffusion coating (LM); (b) Al-Si diffusion coating (SEM)

Coated and uncoated specimens were fatigued in a closed-loop electro-hydraulic testing system at total strain rate of $2x10^{-3}$ s^{-1} with fully reversed total strain cycle (R_ε = -1) at 800 °C in air. Heating was provided by a three-zone resistance furnace and the temperature was monitored by three thermocouples. Strain was measured and controlled using sensitive extensometer with 12 mm base. Hysteresis loops for selected numbers of cycles were recorded in disk memory. Plastic strain amplitude derived from the half of the loop width and stress amplitude at half-life were evaluated.

The hardness was measured in sections perpendicular to the surface in LECO 400M-PC2 indentation tester equipped with the Knoop indenter using a load of 0.025 kgf (0.245 N). Light microscope (LM) and scanning electron microscope (SEM) Philips XL30 were used to study surface relief, fracture surfaces and polished sections of the gauge segment in both treated and untreated specimens.

3. Results and discussion

3.1. Surface layer characterization

Microstructure of surface treated specimens is shown in Fig. 1 in the section perpendicular to the specimen surface both for the Al and Al-Si coating. Both diffusion coatings consist of an outer layer (OL) and a diffusion zone (DZ). The total thickness of the coating ranges in the interval from 65 to 80 µm and from 55 to 70 µm for Al and Al-Si layer, respectively. The mean thickness of the diffusion zone is 22 µm for Al coating and 10 µm for Al-Si one. The Knoop hardness HK 0.025 in OL, DZ and substrate for the Al coating (Al-Si coating) is 731, 636 and 422 (606, 738 and 394), respectively.

3.2. Stress response

The dependence of the stress amplitude σ_a on the number of cycles N obtained for coated and uncoated specimens for different total strain amplitudes is shown in Fig. 2. Fig. 2a shows hardening/softening curves for the uncoated superalloy. The initial hardening followed by saturation and softening is observed in the high amplitude domain while the saturated stress response is typical for low amplitudes. The Al and Al-Si coated material softens for all amplitudes with the exception of the short incipient hardening at high

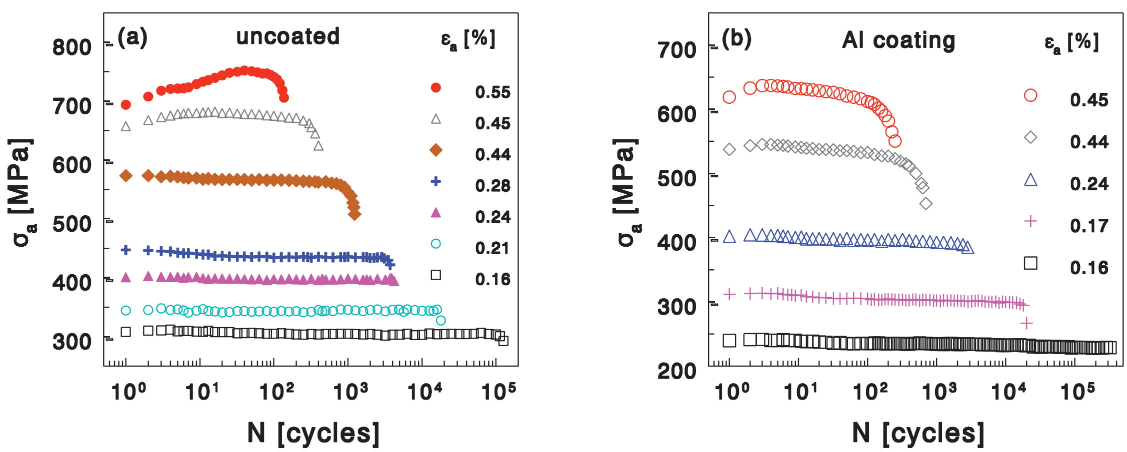

Fig. 2. Fatigue hardening/softening curves of the uncoated (a) and Al coated (b) Inconel 713LC

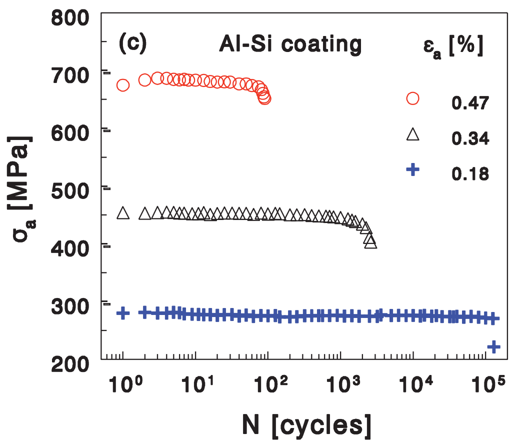

Fig. 2c. Fatigue hardening/softening curves of the Al-Si coated Inconel 713LC

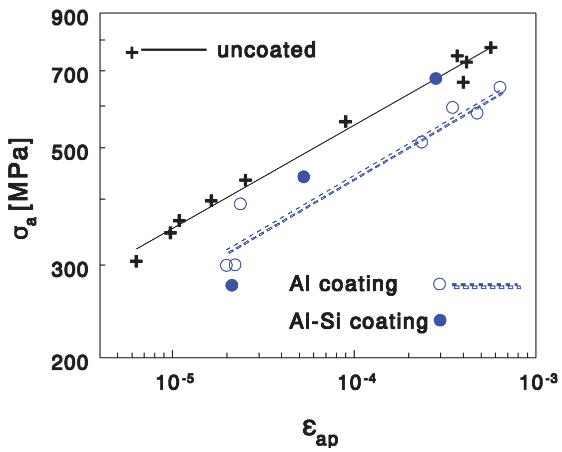

Fig. 3. Cyclic stress-strain curve of the coated and uncoated Inconel 713LC

strain amplitudes – see Fig. 2b and 2c. The softening becomes weaker with decreasing amplitudes.

Cyclic stress-strain curves are shown in Fig. 3 both for the uncoated and coated material. Experimental data were approximated by the power law

$$\log \sigma_a = \log K' + n' \log \varepsilon_{ap}. \qquad (1)$$

and material parameters K' and n' were evaluated using linear regression analysis. Fatigue hardening coefficient K' is equal to 3340 (2820) and fatigue hardening exponent is 0.196 (0.201) for the uncoated (Al coated) superalloy. The stress response of the Al-Si coated Inconel 713LC is almost identical for high amplitudes and lower in the low amplitude domain in comparison with the uncoated material – see Fig. 3. This behavior agrees well with data published recently in the different heat of Inconel 713LC with the Al-Si diffusion coating made by another producer [3]. Recent study on the effect of the annealing applied during the diffusion coating on the structure of precipitates in the basic material shows a tendency of precipitates to elongation and coarsening during the exposition of Inconel 713LC to high temperatures [3]. The structure coarsening contributes to the stress response decrease of the coated superalloy.

3.3. Fatigue life

Fatigue life curves of the surface treated and untreated superalloy are plotted in Fig. 4. Fig. 4a shows the plastic strain amplitude ε_{ap} at half life vs. the number of cycles to fracture N_f in the bilogarithmic representation. Experimental data were fitted by the Manson-Coffin law

$$\log 2N_f = (1/c) \log \varepsilon_{ap} - (1/c) \log \varepsilon_f' \qquad (2)$$

and material parameters were evaluated using non-linear regression analysis. Fatigue ductility coefficient ε_f' is equal to 0.039 (0.10) and fatigue ductility exponent is -0.78 (-0.84) for the uncoated (Al coated) superalloy. It can be seen from Fig. 4a that the Al coating results in the fatigue life improvement in the

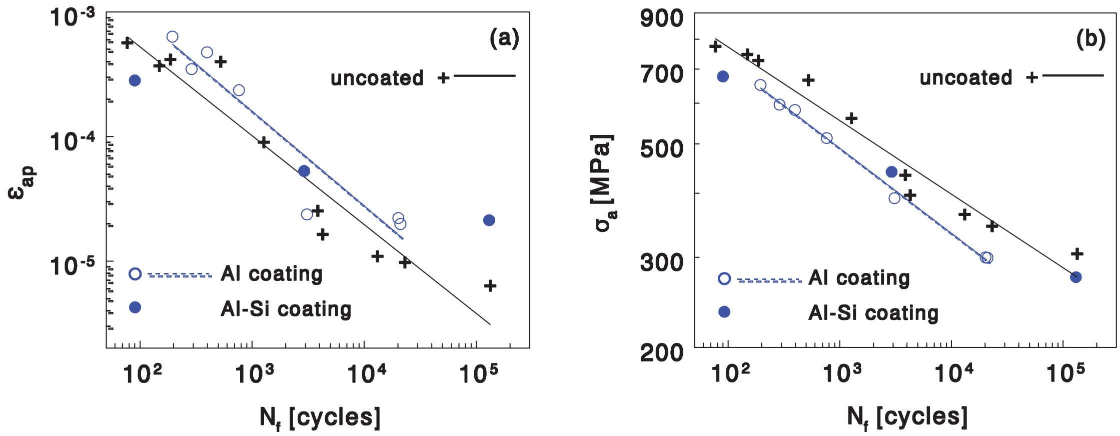

Fig. 4. Fatigue life curves of Inconel 713LC with Al and Al-Si coatings; (a) Manson-Coffin and (b) Basquin diagram

Manson-Coffin representation. The Al-Si coating increases the fatigue life at low amplitudes and decreases it in the high amplitude domain.

Fatigue life curves in the representation of the stress amplitude σ_a at half-life vs. the number of cycles to fracture N_f are shown in Fig. 4b. Experimental data were fitted by the Basquin law

$$\log 2N_f = (1/b) \log \sigma_a - (1/b) \log \sigma_f' \qquad (3)$$

and parameters were evaluated using non-linear regression analysis. Fatigue strength coefficient σ_f' is equal to 1740 MPa (1740 MPa) and fatigue ductility exponent is -0.150 (-0.167) for the uncoated (Al coated) superalloy. Fig. 4b shows slight detrimental effect of the Al coating on the Basquin curve. The Al-Si coating decreases the fatigue life only for the high amplitudes.

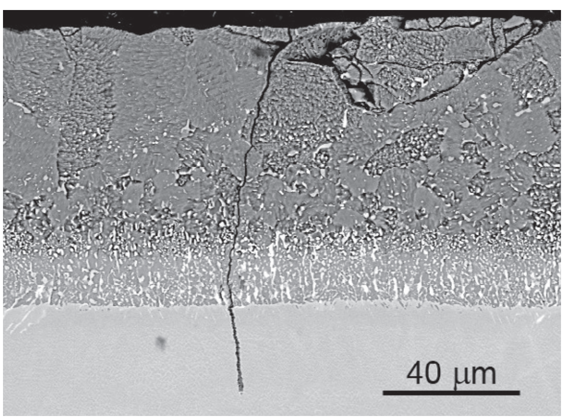

Fig. 5. Fatigue crack growing from the surface to the substrate of an Al coated specimen. Section perpendicular to the specimen surface (SEM)

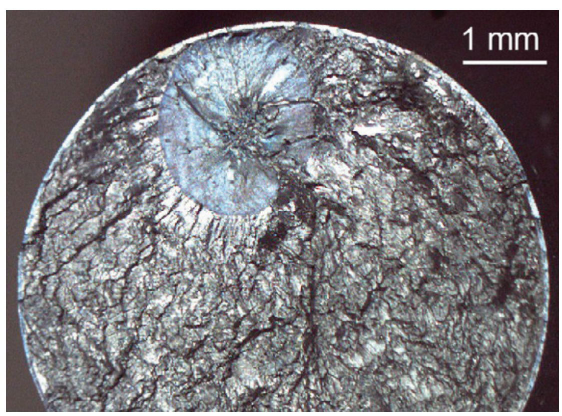

Fig. 6. Optical micrograph of fracture surface of a coated specimen with subsurface fatigue crack initiation

3.4. Specimen section and fracture surface observations

A SEM micrograph of the section parallel to the loading axis of an Al coated specimen cycled to fracture with the high strain amplitude (ε_a = 0.45 %, N_f = 397 cycles) is shown in Fig. 5. It can be seen from Fig. 5 that a fatigue crack goes through the coating to the substrate and stops here. Specimen section observations showed that the surface crack initiation occurred both in coated and uncoated Inconel 713LC at all strain amplitudes studied.

Figure 6 shows the fracture surface of an Al-Si coated specimen cycled to fracture in the low amplitude domain (ε_a = 0.18 %). Subsurface crack initiation from a defect present in the material is clearly visible. Fracture surface observations reveal that the crack initiation at casting defects is decisive for the fatigue damage evolution both in surface treated and untreated Inconel 713LC.

Present results show that the Al diffusion coating increases the fatigue life of Inconel 713LC in the Manson-Coffin representation – see Fig. 3a. The main crack initiates preferably at casting defects. Since surface defects are covered by the coating the crack initiation becomes more difficult because it is subsurface and in oxygen-free environment. This results in the life extension in comparison with the uncoated material.

4. Summary and conclusions

(i) The stress response at half-life of the Al and Al-Si coated material is lower than that of the uncoated superalloy at the same strain amplitude.

(ii) The Al diffusion coating has beneficial effect on the fatigue life of Inconel 713LC in the Manson-Coffin representation. This applies to the Al-Si diffusion coating in the low amplitude domain.

(iii) The fatigue life curve of the Al coated material in the representation of the stress amplitude vs number of cycles to fracture is shifted to the lower fatigue life in comparison with the uncoated one. This is true for the Al-Si coating for high amplitudes.

Acknowledgements

The research was financially supported by the project MEB0810123 of Ministry of Education, Youth and Sports and by the grants Nos. 106/09/P522 and P107/11/2065 of the Grant Agency of the Czech Republic and the grant No. 2E13800119 of the FME BUT.

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